

Effect of Air Swirler Configuration on Lean Direct Injector Flow Structure and Combustion Performance with a 7-point Lean Direct Injector Array

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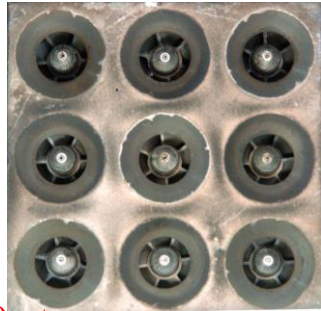
Motivation—Reduce Aircraft NOx emissions



Lean Direct Injection (LDI) has been demonstrated as a way to reduce aircraft combustor NOx emissions while keeping CO and UHC's at current levels. It has been successfully used in NASA-sponsored programs.

The multiplex LDI scheme: **uniform f/a to keep flame temp low**

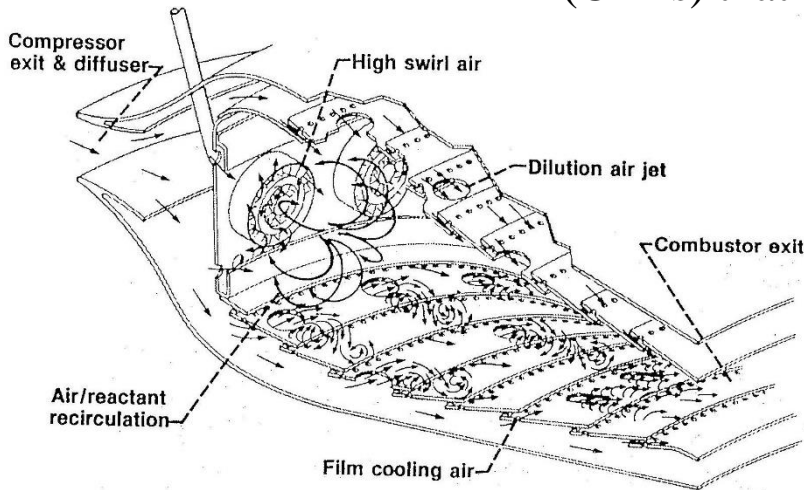
- Requires fine atomization and rapid mixing to assure fuel-air uniformity
- Inject fuel directly into the flame zone
- To enhance rapid mixing, several small fuel-air elements replace one injector and help shorten flame zone
- Use **high swirl air** to generate central recirculation zones (CRZs) that help anchor the flame.



9-pt



7-pt



A couple problems:

- Lean combustion generally may be susceptible to dynamics that destabilize the combustor.
- Early LDI performed well at high power, but had limited flame stability at low power conditions

- FULLY 3-DIMENSIONAL FLOW
- HIGH TURBULENCE LEVELS
- CHEMICAL REACTION/HEAT RELEASE
- 2 PHASE WITH VAPORIZATION

Current objectives

One goal for the 7-point LDI experiments is to quantify the effect of air swirl angle on recirculation, fuel-air mixing, combustion emissions and flame tube combustor operability.

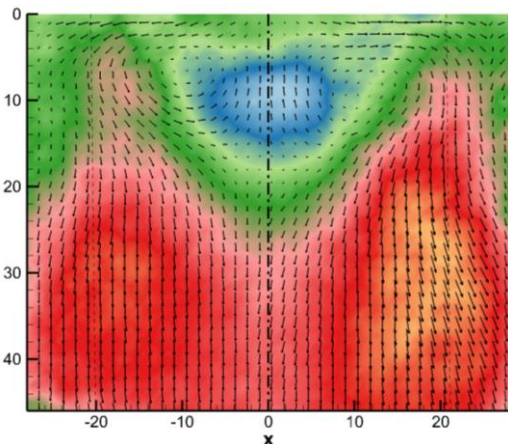
Another goal is to analyze combustion dynamics to help guide us toward suitable fuel injector designs.

This paper describes:

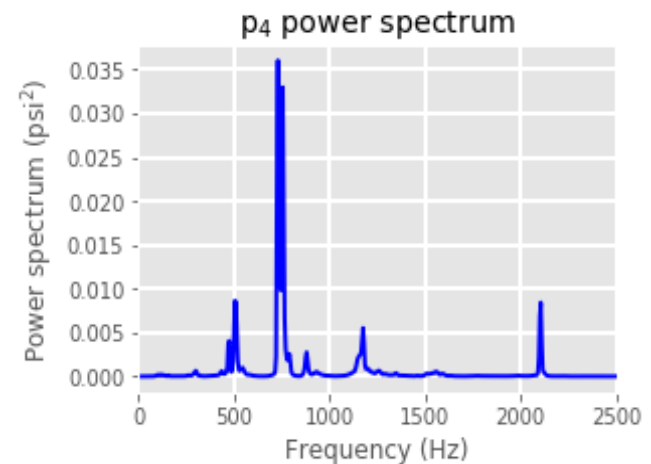
1. Cold flow velocity measurements to determine central recirculation zones for several configurations of the 7-point, in which we varied air swirler angles and positions
2. Initial explorations of combustion dynamics for a subset of the cold flow configurations

Axial
velocity
contour

Blue =
Reverse
flow



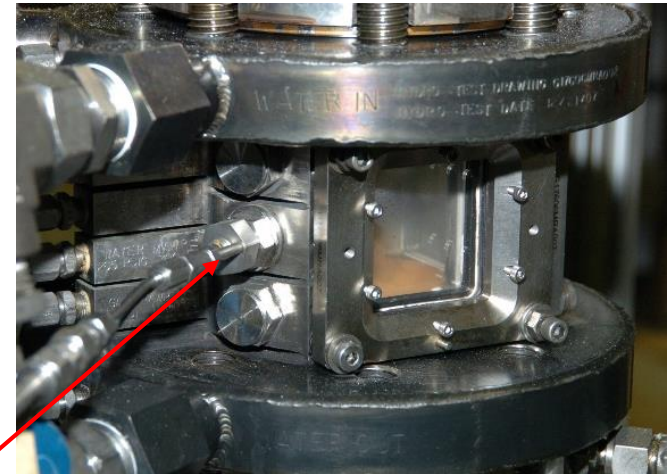
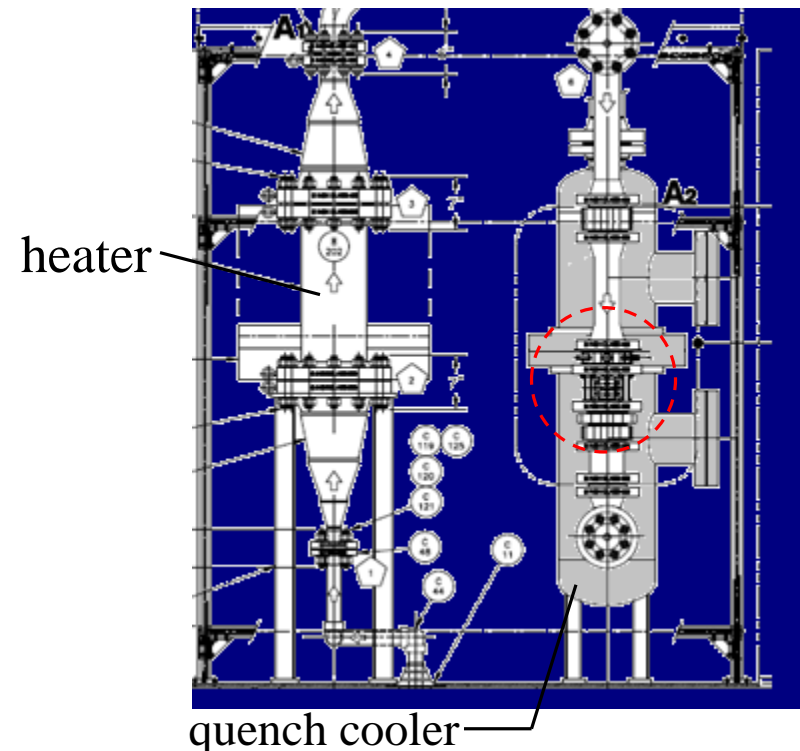
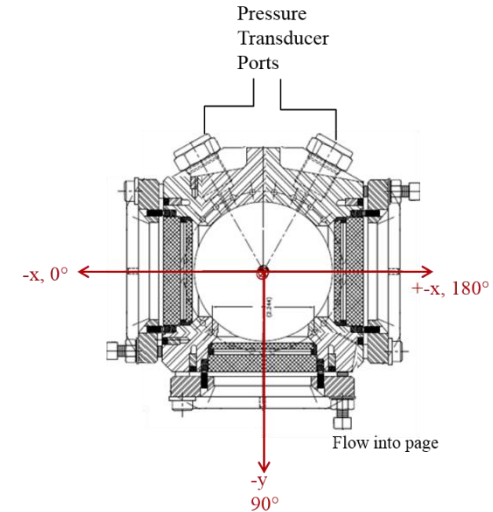
flow
↓



Combustion and Dynamics Facility



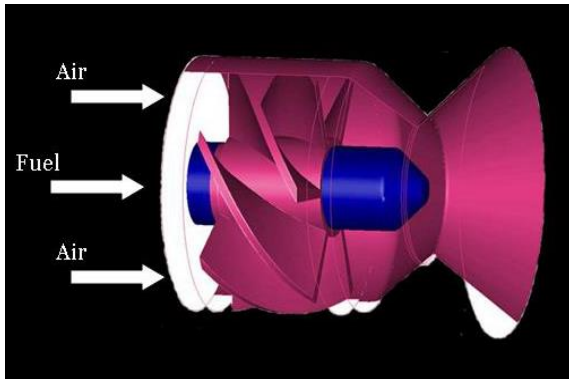
- Vertical flow through combustor (top to bottom)
- Inlet temperature: 300-810 K (70-1000 °F)
- Pressure: 101-517 kPa (15-75 psia)
- Pressure ports to support combustion dynamics (these tests did not have choked inlet or exit)
- Supports fuel staging-two fuel circuits
- Conventional (Jet-A) and alternative jet fuels



PCB sensor

- Three 2.3-in x 2.4-in windows
- 3-in diameter cross-section

Baseline LDI element



- Six helical angled vanes
- Simplex atomizing nozzle
- Converging-Diverging Venturi

Swirlers: 45°, 52°, 60°

Swirl #s: 0.59, 0.77, 1.02

- 76.2 mm overall diameter
- 23.8 mm between adjacent elements
- Center can be offset upstream to act as a “pilot”

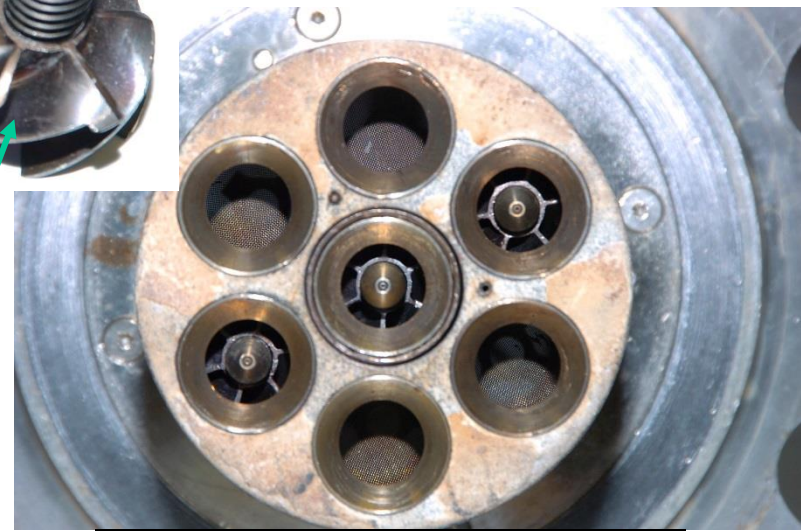
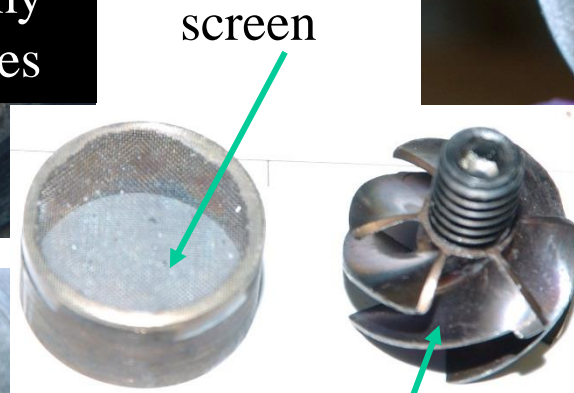
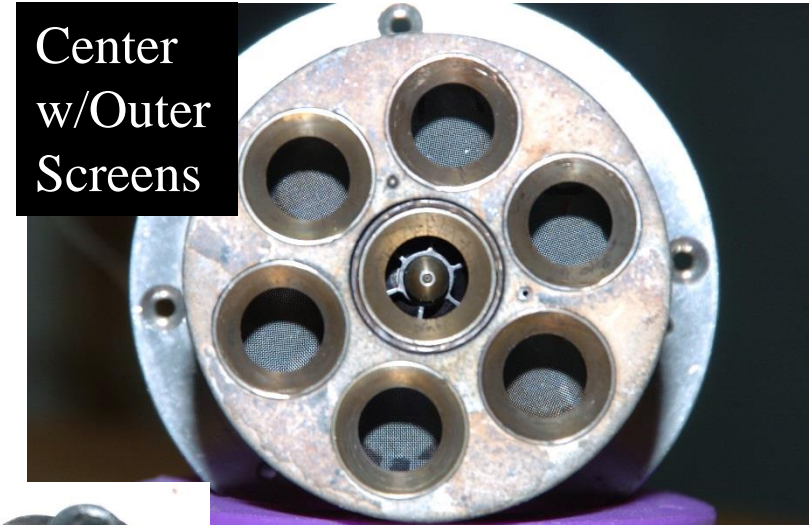
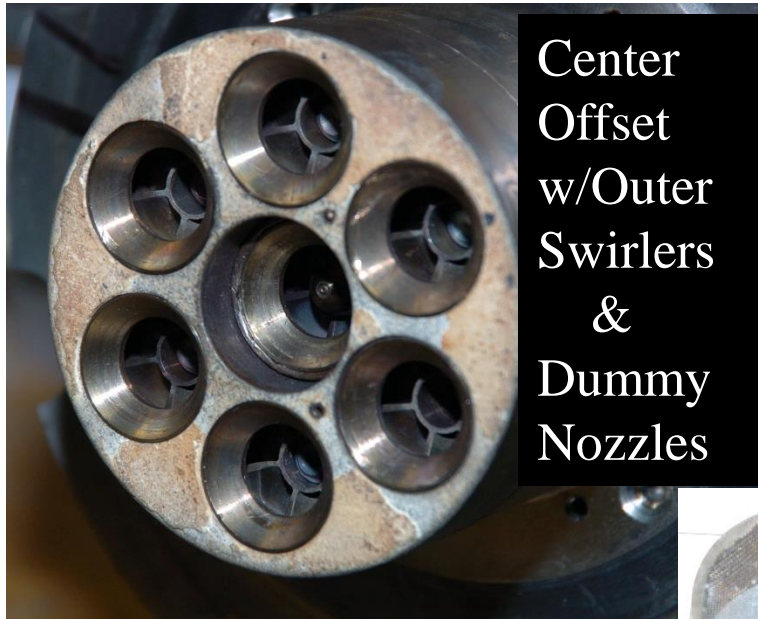


Background:

Recent 7-point LDI History

- We used three axial air swirlers, having angles of 60° , 52° , and 45° , with swirl numbers of 1.02, 0.77, 0.59
- Determined that only the 60° air swirler can generate a Central Recirculation Zone (CRZ) for this swirl-venturi hardware
 - Observed for 9-point LDI in all cases tested
 - For 1-LDI, neither 45° nor 52° produced enough angular momentum to provide recirculation. Instead, the axial flow accelerated through the venturi however—
 - Spacing and/or array-structure determines whether the CRZ forms
 - For 7-point, there seems to be strong interaction very close to the dome, likely indicating the spacing is too close to produce, though there may be other geometrical factors also influencing the flow field such as array configuration
- We began a study to help determine why we were not seeing a CRZ using all 60° swirlers in the 7-point LDI

Hardware Configuration Examples



7-pt LDI Hardware Configurations and Orientation with respect to the Camera

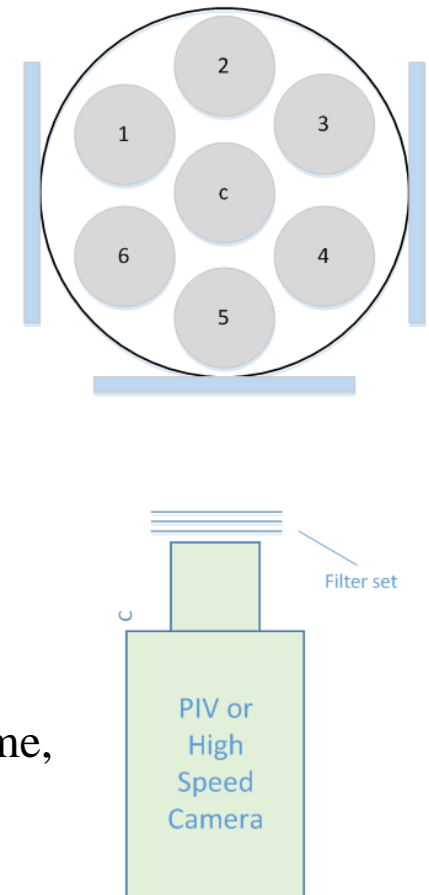


7-pt swirler configuration variations used

<i>Designation</i>	<i>Center Swirler</i>	<i>Outer Swirlers</i>
LH60all	LH 60°	LH 60°
LH60all_offset	Offset LH 60°	LH 60°
RH60c-1-3-5_LH60-2-4-6	RH 60°	Alternating RH60/LH60
RH60c-1-3-5_RH45-2-4-6	RH 60°	Alternating RH60/RH45
RH60coff_RH45o	Offset RH 60°	RH 45°
RH60c_RH45o	RH 60°	RH 45°
LH60c_RH45o	LH 60°	RH 45°
RH60c_RH52o	RH 60°	RH 52°
RH52all	RH 52°	RH 52°

Since it is air swirl effects we are considering, if all are clocked the same, handedness does not matter

LDI orientation relative to camera



Non-reacting results to examine CRZ formation



Velocity measurements using PIV, water-seeded via center nozzle

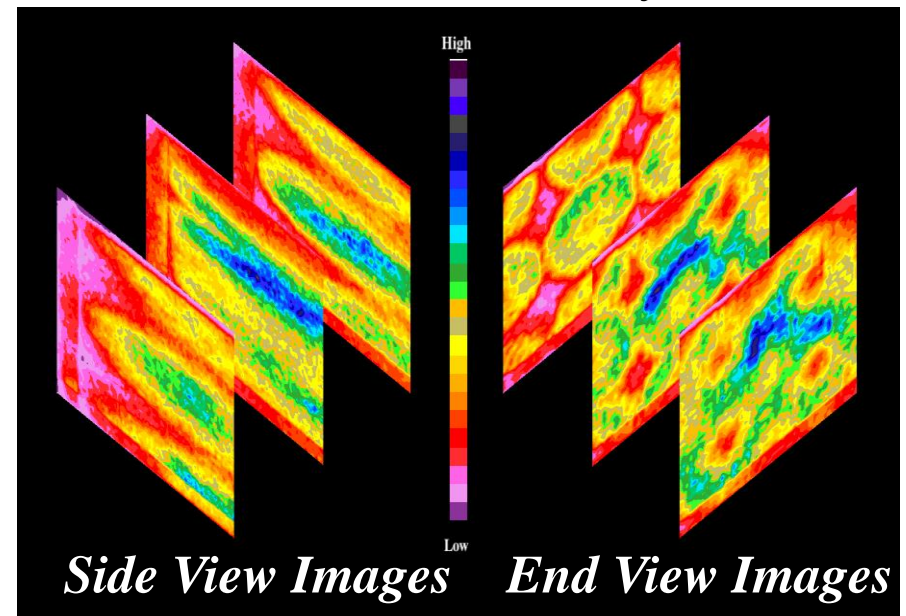
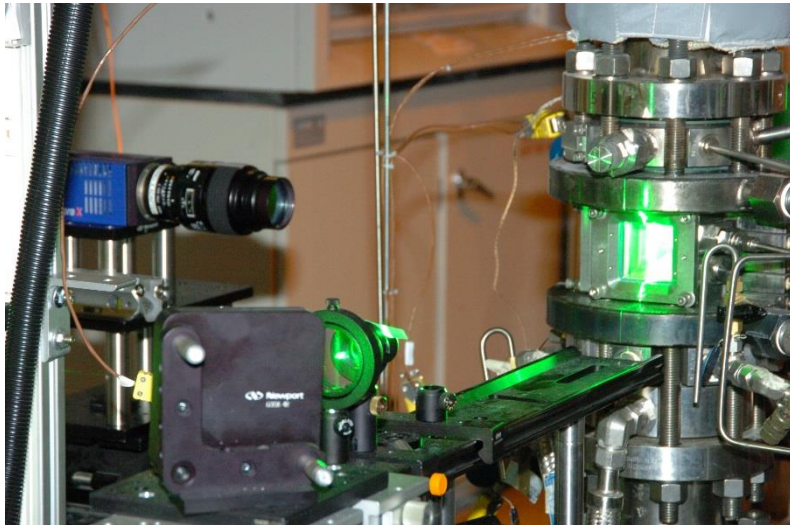
-Water flow rate to match fuel flow rate by volume

Air inlet conditions: 5-bar, 700K, reference velocity = 22.9-m/s

Each resultant field is average of 500 image pairs, $\Delta t \cong 6\mu\text{s}$

Traversed across the flow in mm increments from $y = -24$ to $+24$

Water seeding keeps windows clean \therefore time to collect data at many locations

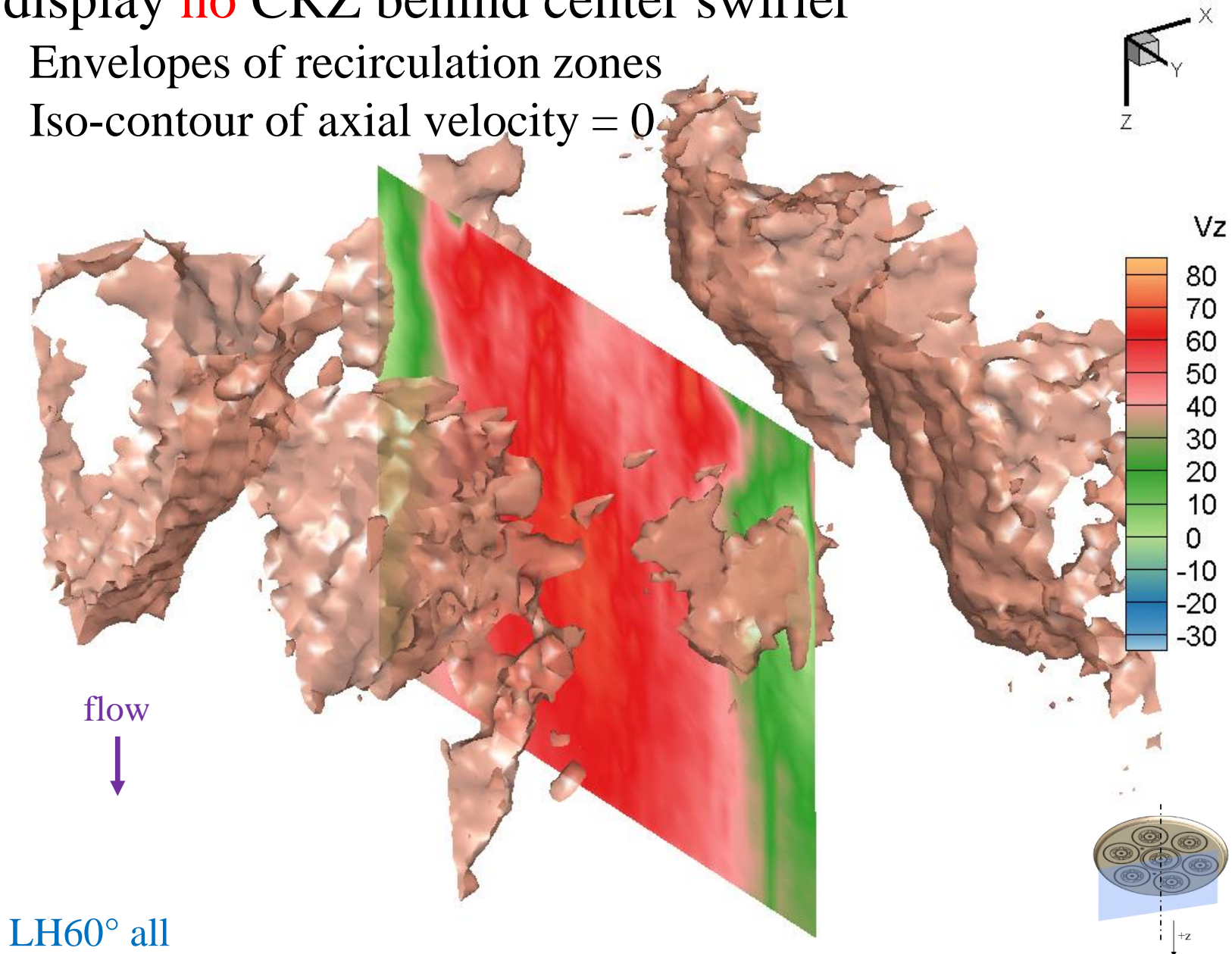


Cold Flow Example Results:

- A look at CRZ formation for configurations that do not have a center swirler CRZ
- Look at CRZ formation for configurations that have a center swirler CRZ
 - Compare center CRZ size and average velocity within the CRZ

Configurations having 60° in center and outer positions display **no** CRZ behind center swirler

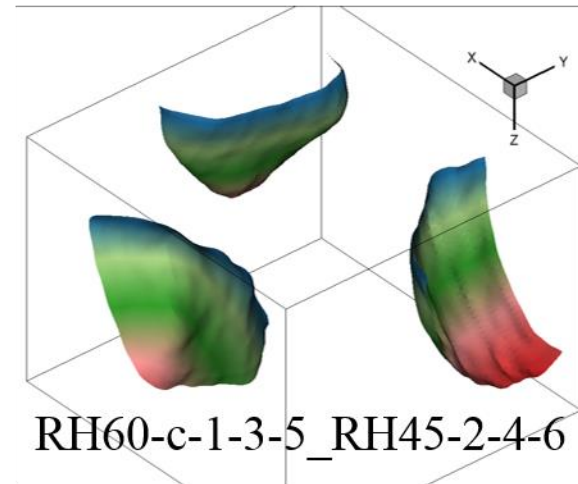
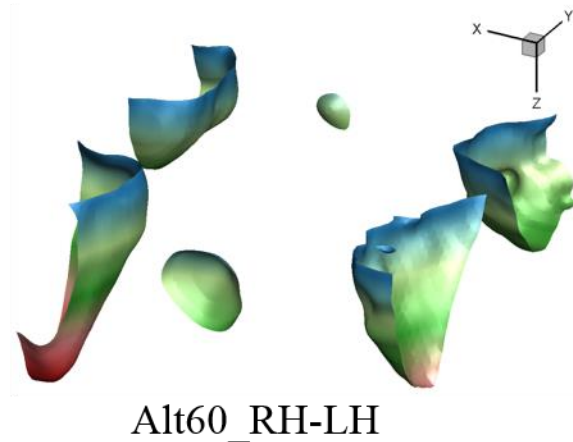
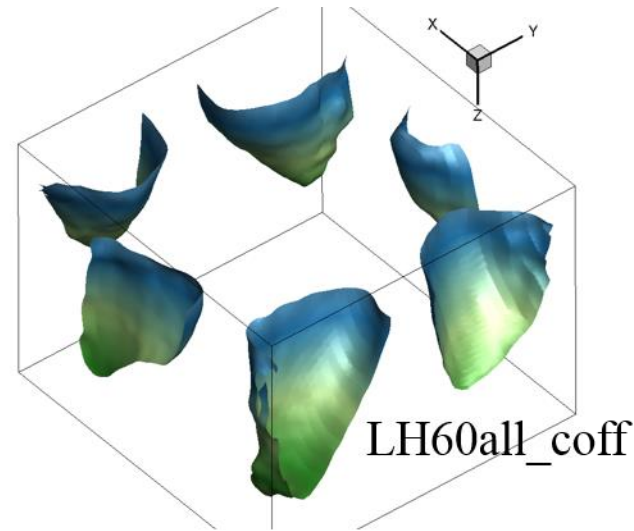
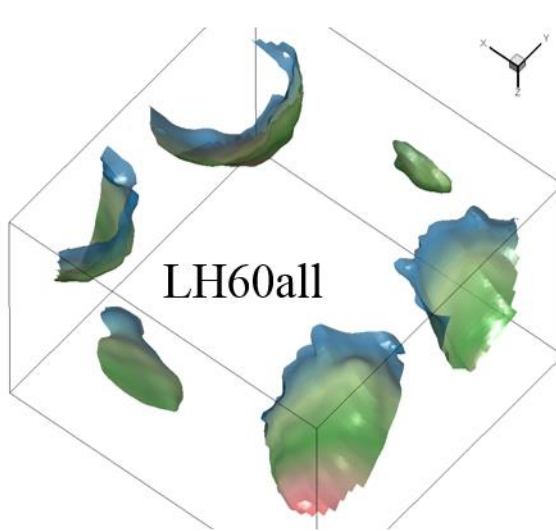
- Envelopes of recirculation zones
- Iso-contour of axial velocity = 0



Overview of configurations with 60° center and outer swirlers



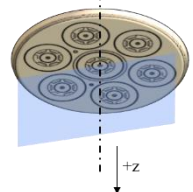
Iso-contours of axial velocity = 0



Closest to dome



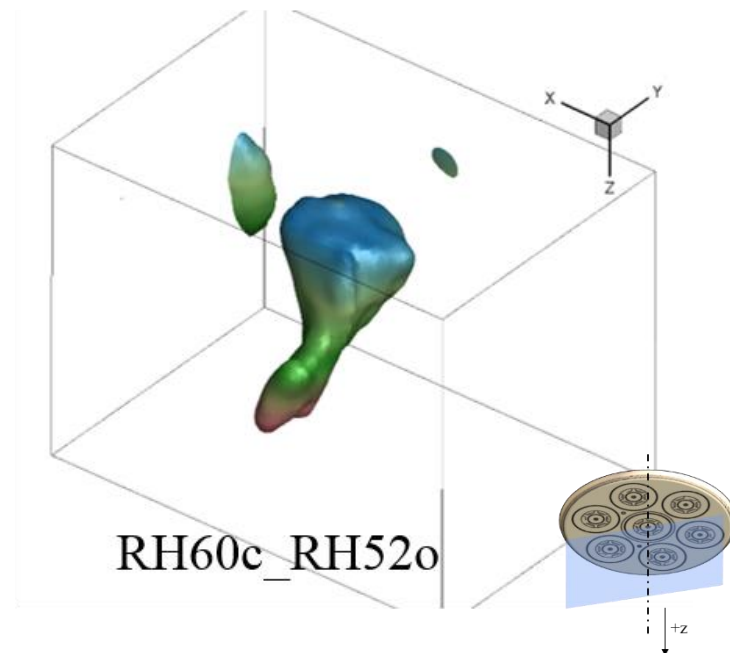
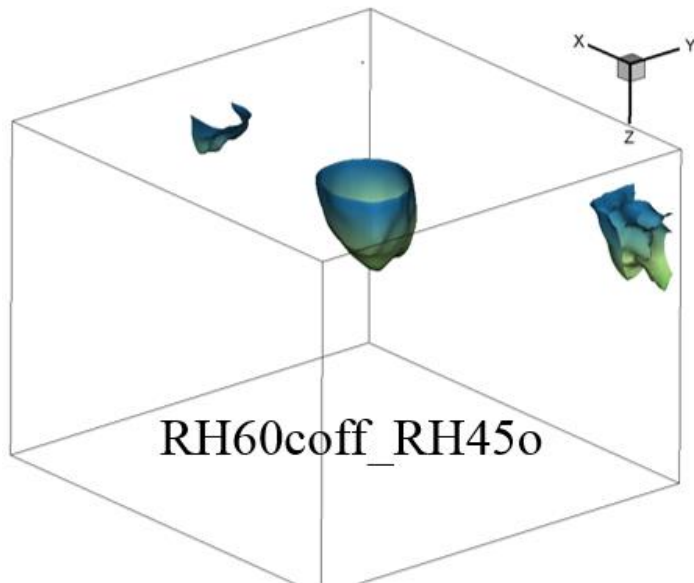
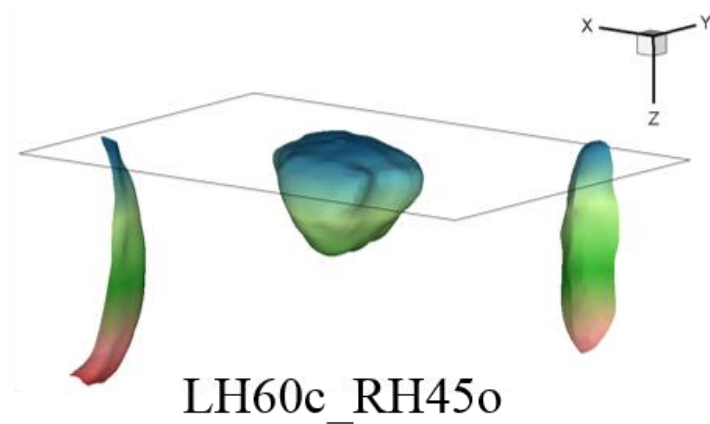
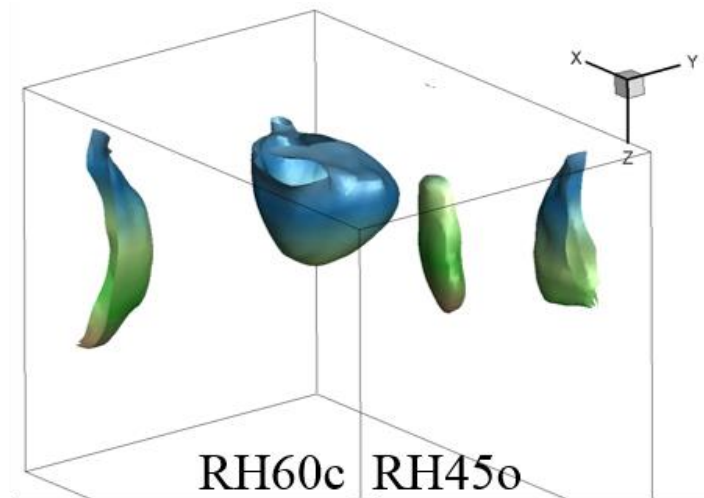
Farthest from dome



flow
↓

Center swirler CRZ

Iso-contours of axial velocity = 0

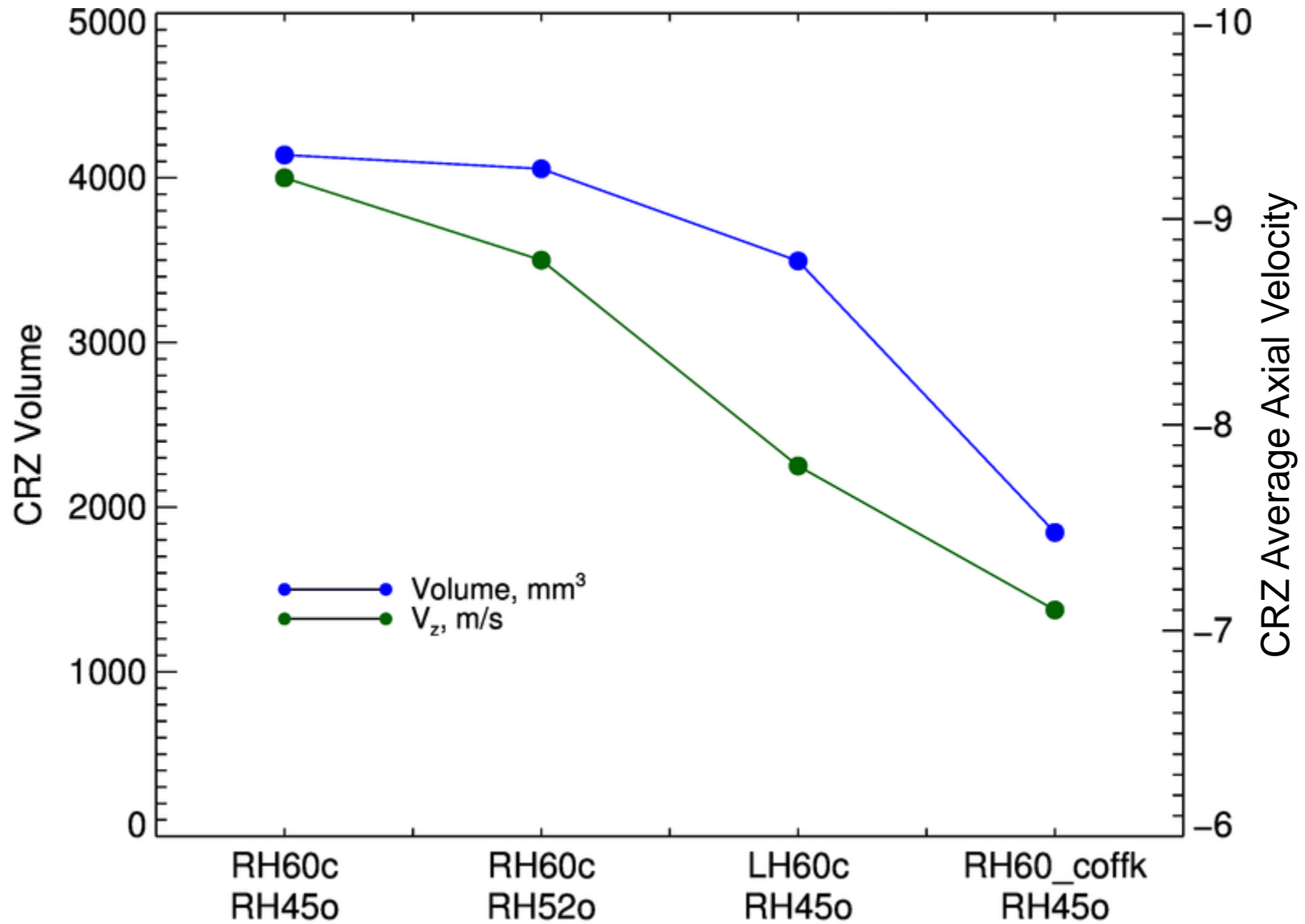


Closest to dome



Farthest from dome

Center Swirler CRZ: Volume and Average Axial Velocity





Summary for cold flow velocity measurements

- Of the three swirlers, only the 60° swirler ($SN = 1$) produced a CRZ
- The close spacing of swirler elements in the array definitely leads to interactions between swirlers
- Recessing the center element helps to isolate it from the surrounding swirlers
- Using counter swirl helps to isolate the swirlers
- Inter-element spacing affects the size and strength of the CRZs



Burning results—combustion dynamics

Two types of instrumentation used evaluate dynamics

1. PCB sensor, flush mounted. Data Translation acquisition system, 60-kHz
 2. High speed camera. Frame rate: 40kHz
-
- Present results derived from both types of instrumentation
 - Select a frequency for further study and focus on the optical data

Combusting results—Power Spectra

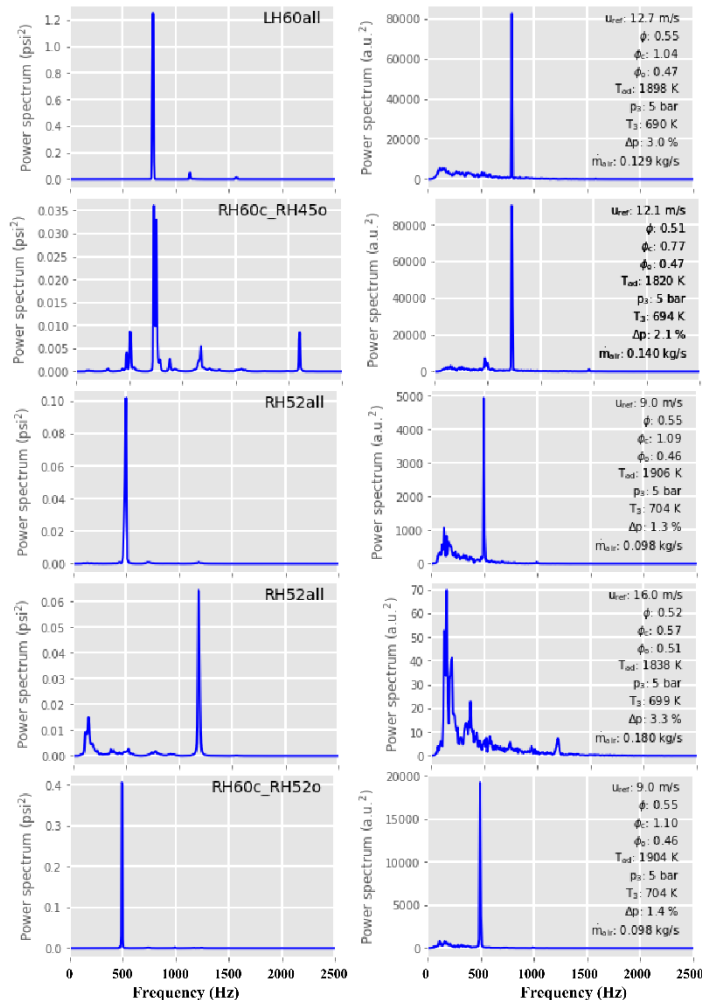


Processing:

- The 0.01-sec rolling mean was subtracted from the original signal. (Image sig = sum of all pixels)
- Power spectrum calculated using entire time signal and normalized so the power spectrum sum = RMS^2

P4 power spectra

Flame luminosity power spectra



- ✓ Similar results from each instrument. There were three consistent dominant frequency ranges: 400-500 Hz, 700-800 Hz, 1100-1200 Hz. Some frequencies are stronger in one versus the other.
- For the two configurations that use 52° swirlers, we saw strong peaks at 500-Hz and the same inlet condition, 500-Hz conveniently is an integer factor of 40,000 Hz (use every 80th frame), so we further explored those two cases using the high speed camera images.
- Comparing these configurations is also nice because one has no CRZ and the other has just the single center CRZ.

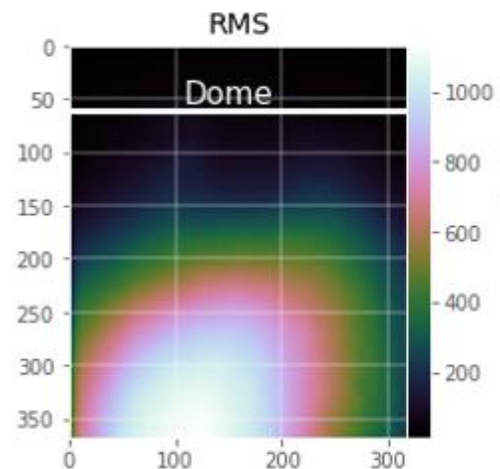
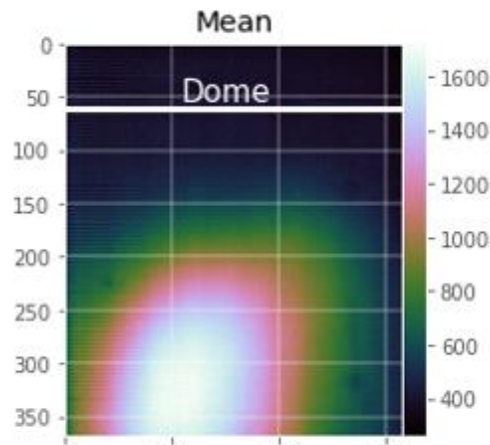
Image statistics derived from the two configurations



Using 48560 individual images each

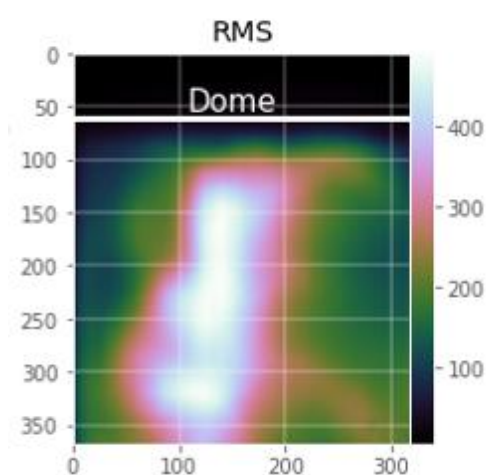
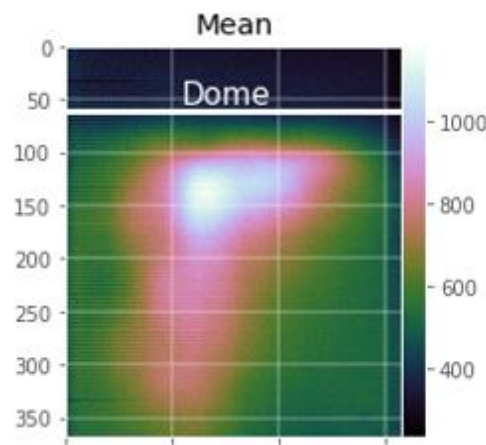
RH52° all

Burns mostly downstream



RH60°c_RH52°o

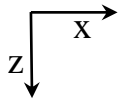
Burns close to dome



Light emitted mainly from C2*, CH* radicals

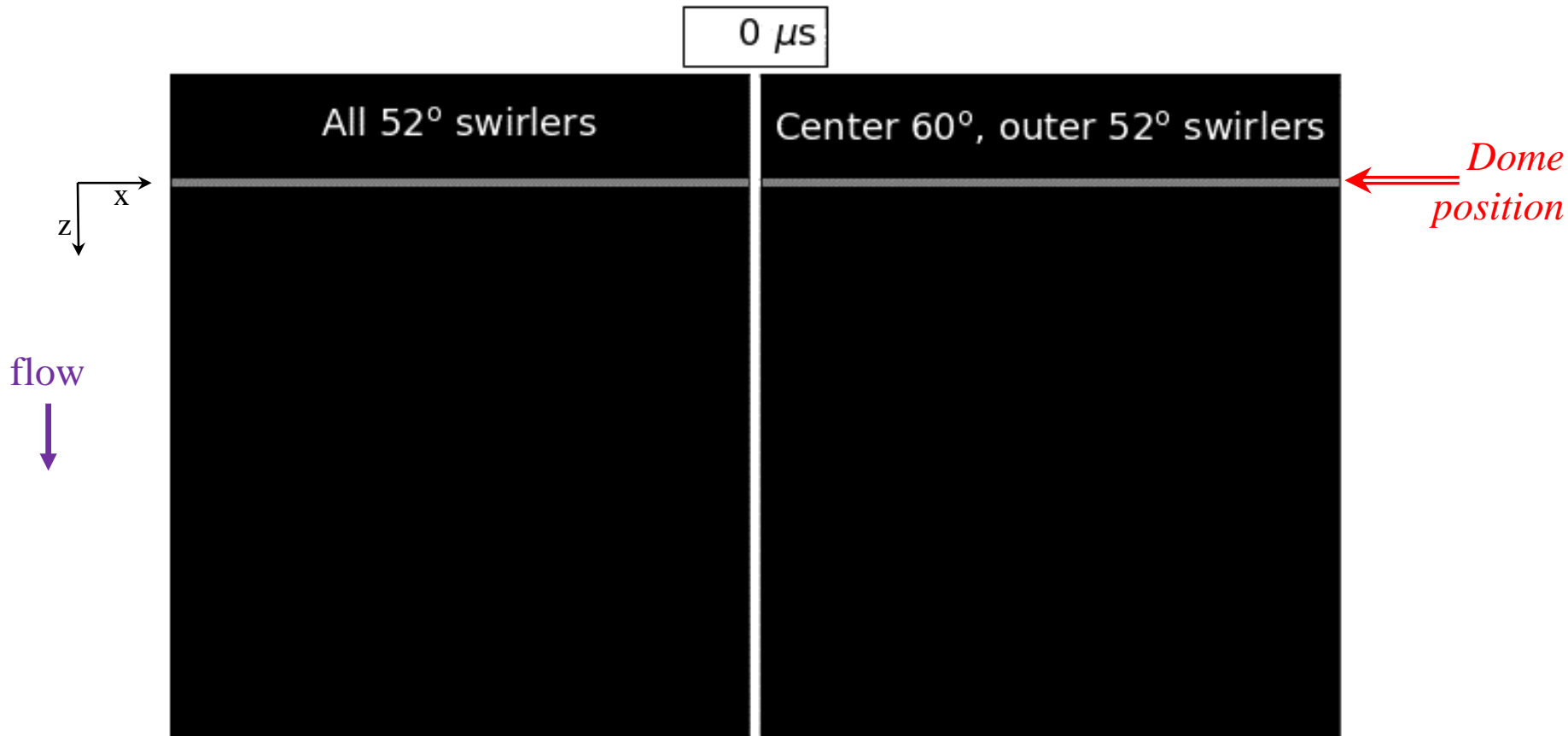
Luminous signal begins for RH52all on average about 22-mm from the dome

Luminous signal for RH60cRH52o begins within 5-mm of dome



High Speed movies from two configurations

Frame rate: 40,000 Hz Time between frames = 25- μ s



See light mostly downstream

- Luminosity nearly always near dome
- Can observe by eye center recirculation

Isolating 500 Hz frequency—resampling the 40,000 Hz image set

Example, using RH52all:(We chose a starting point with low overall luminosity)

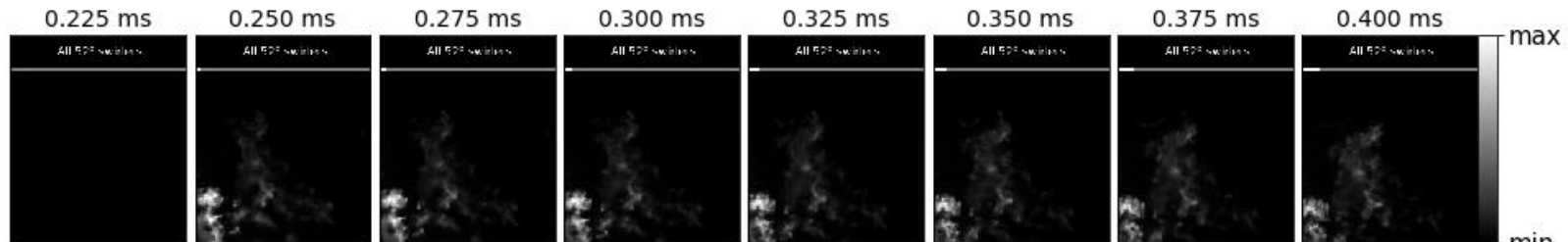
Begin at $t = 0$, ensemble-average every 80th image, subtract overall mean

Each ensemble average corresponds to $48560 \div 80 = 607$ images

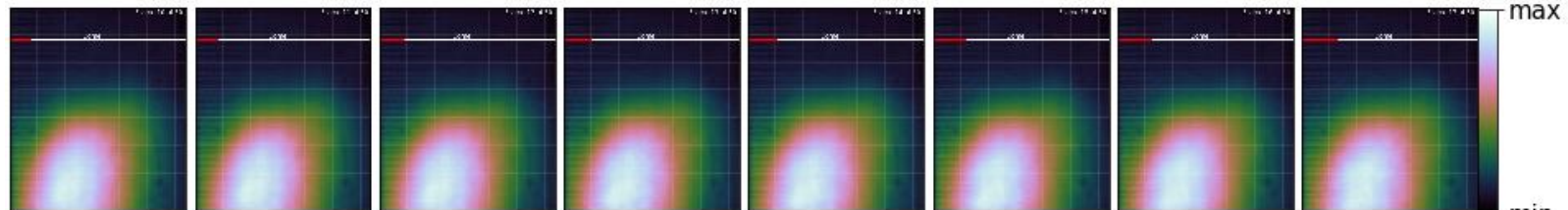
Move to time $t+0.025\text{ms}$ and repeat above. Continue process 78 more times

Example subset beginning at $t = 0.225\text{ ms}$

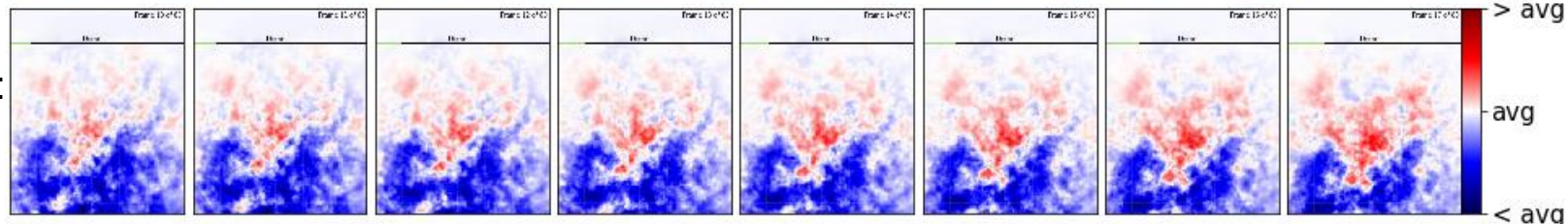
A single
original
image



Ensemble-
Average (EA) of
607 images



Difference images:
EA - Overall mean





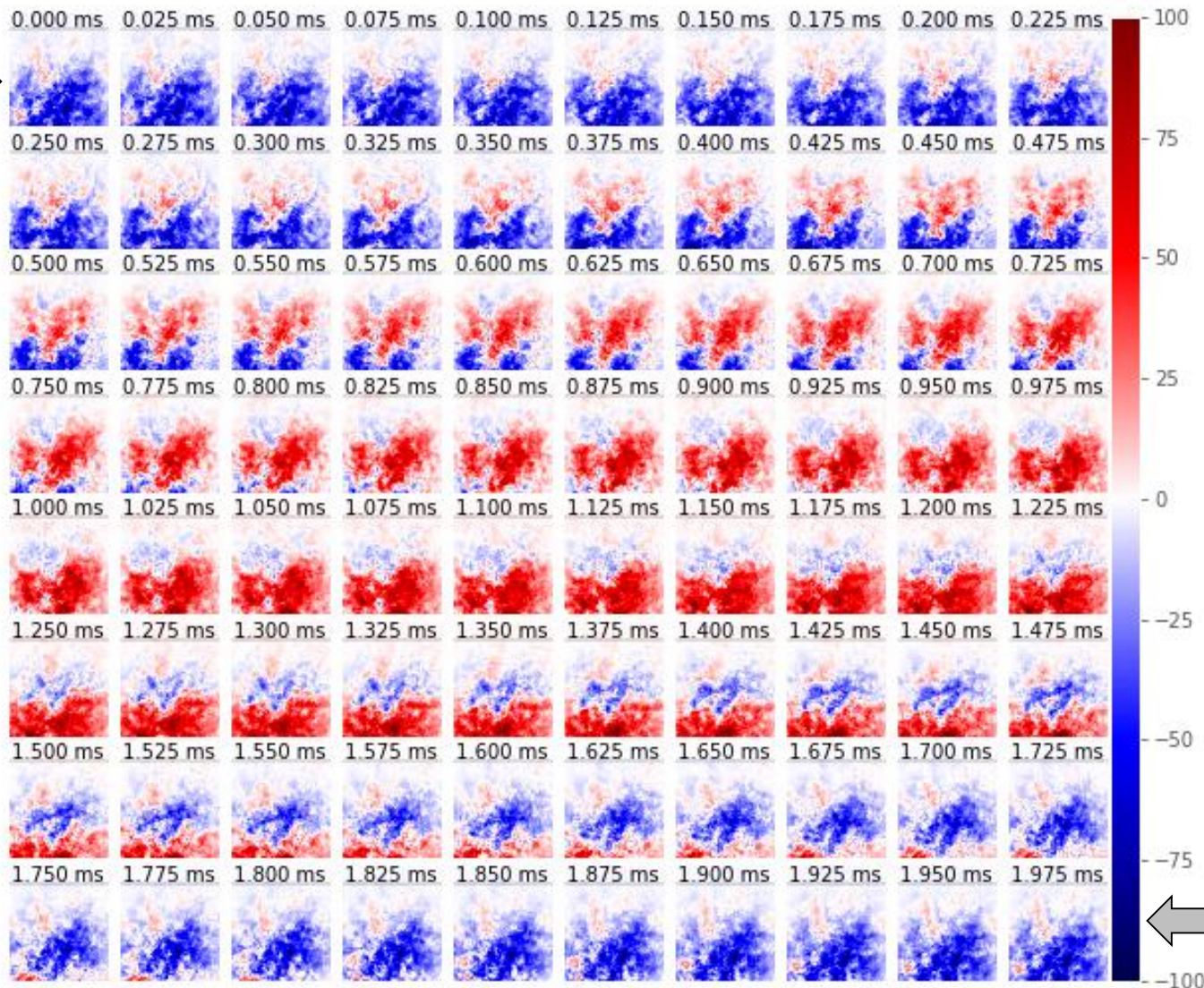
The entire 500-Hz resampled 80-image sequence for RH52all

- Helps emphasize the oscillatory nature of the flame luminosity
- Shows fine structure

Begins with low
luminosity



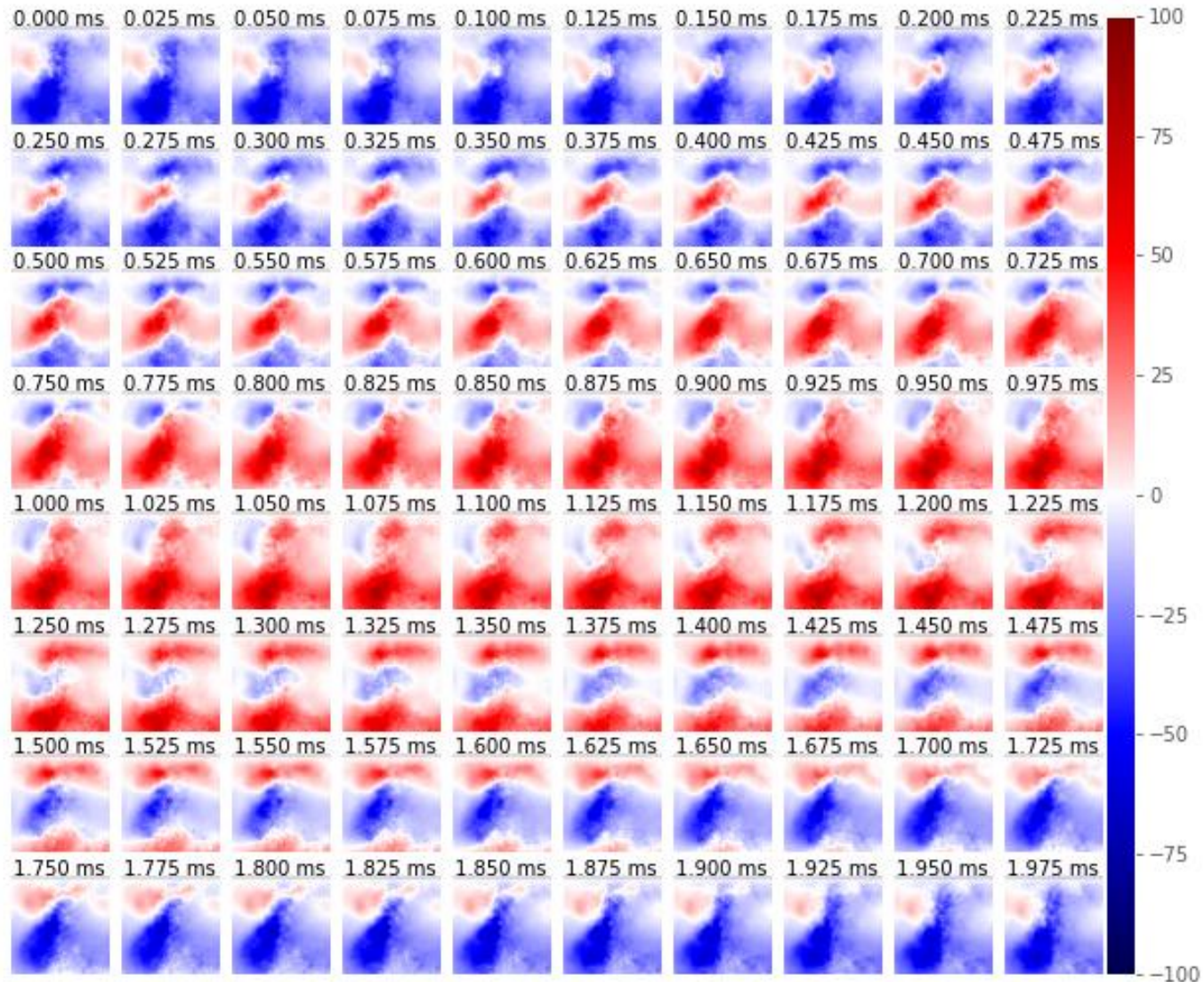
Luminosity
peaks mid-
sequence



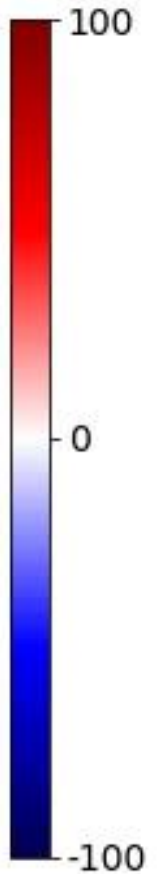
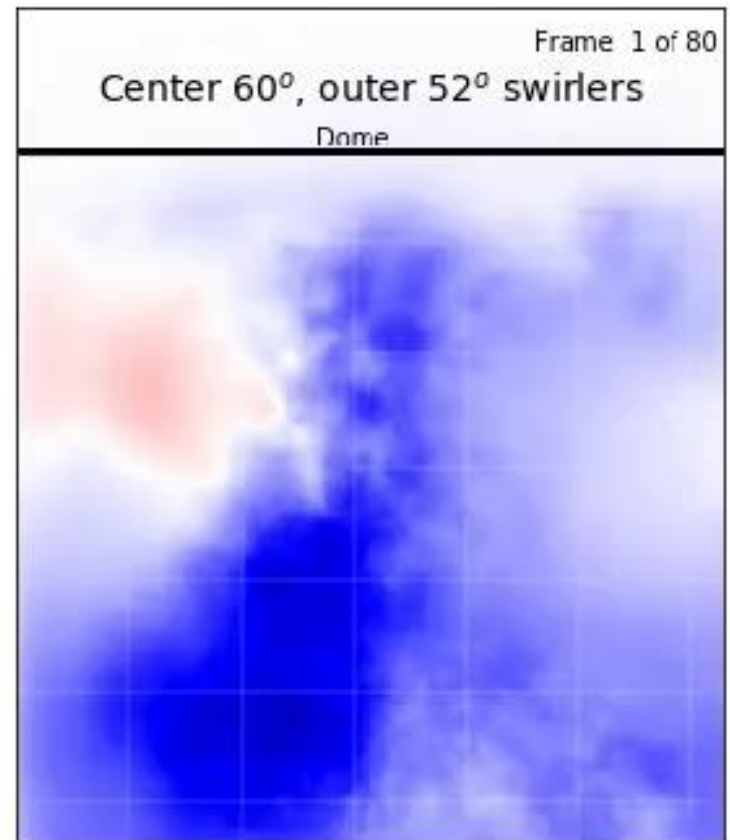
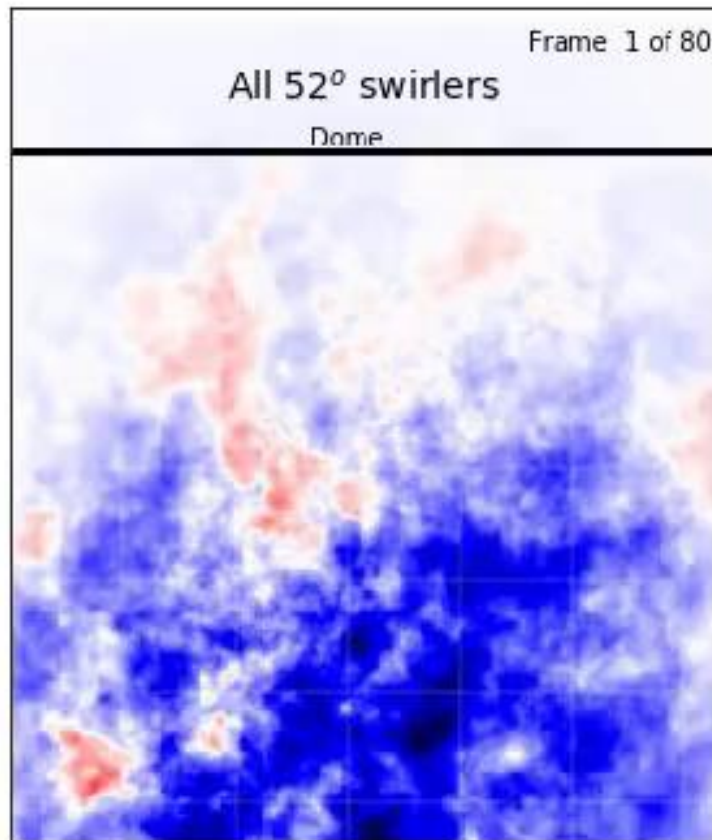
Ends with low
luminosity

The sequence for RH60c_RH52o

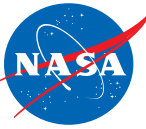
- Like the all 52° swirler configuration, this configuration shows the oscillatory nature of the luminescence
- Difference is that the structure revealed appears more coherent



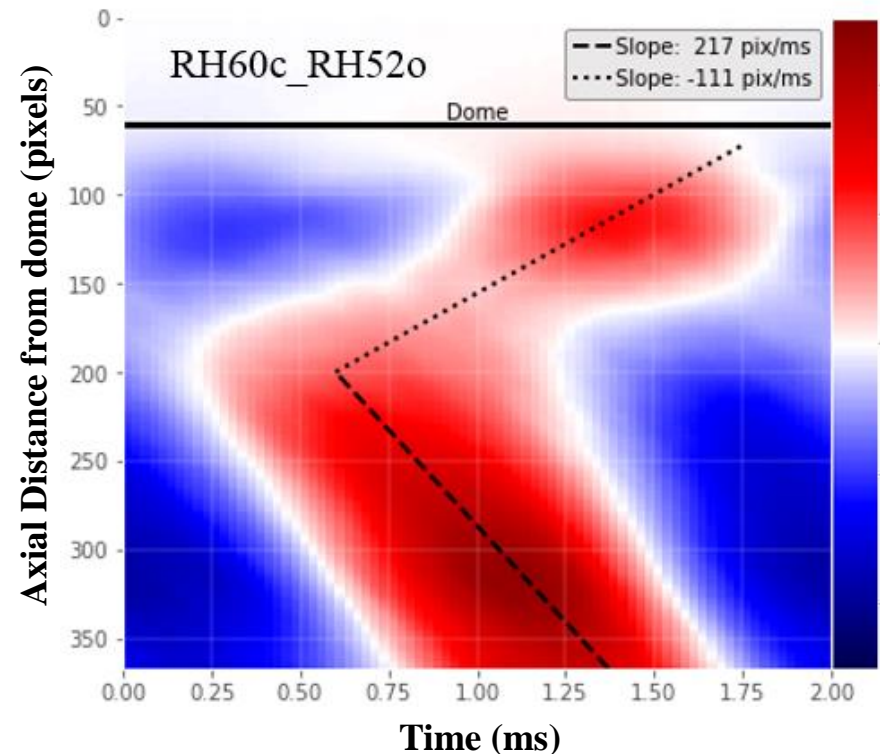
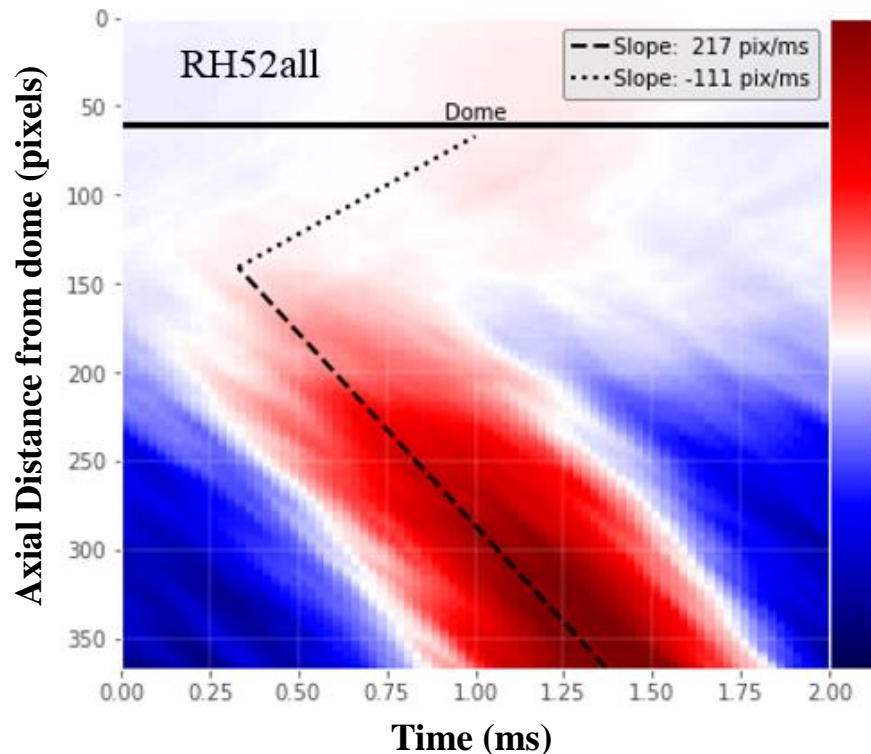
The difference images played in sequence



Use image sequence to track the rate of motion based on luminosity



- 80 columns make up the graphs below, from time $t = 0$ to time $t = 1.975$ ms
- Sum up the rows of each image to produce a single column vector for each time step
- Provides a graphical way to visualize/describe flame motion



- Flame front moves downstream at rate of roughly 33-m/s
- Flame front moves upstream at about 16-m/s



Summary—combusting dynamics results

- We presented results obtained by spectral analysis of five configurations, with a focus on exploring 500-Hz events.
- Pressure measurements and optical measurements had similar frequency results
- Using the high speed camera, we also have identified another method to reveal flow structure at frequencies of interest and can possibly use this method to determine flame speeds. We expect to explore this method further to help possibly identify sources of dynamics.



Acknowledgment

- The NASA Transformational Tools and Technologies Project supported this work.